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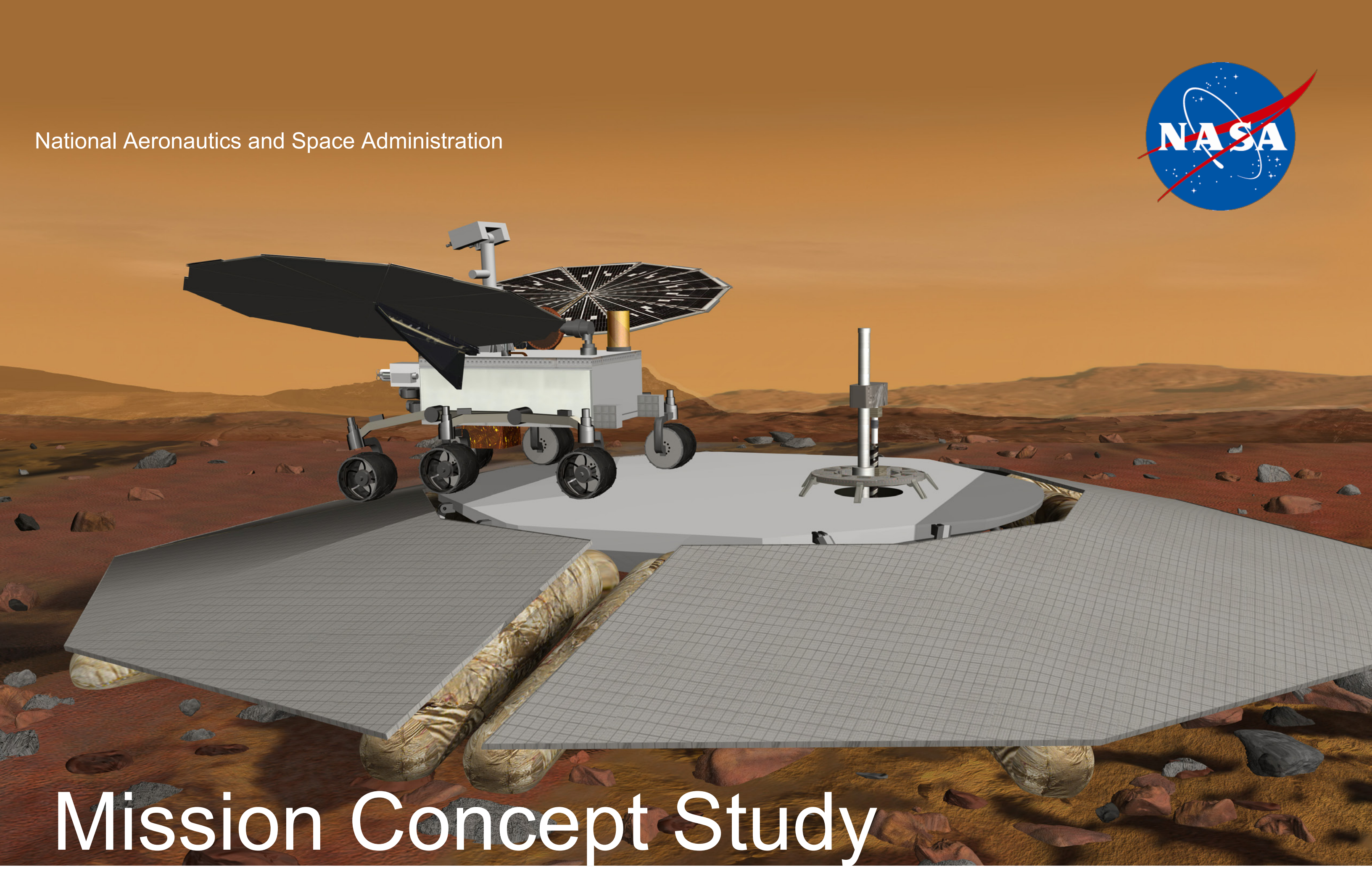

Mission Concept Study

Planetary Science Decadal Survey
Mars 2018 Sky Crane
Capabilities Study

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Data Release, Distribution, and Cost Interpretation Statements

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Cost reserves for development and operations were included as prescribed by the NASA ground rules for the Planetary Science Decadal Survey. Unadjusted estimate totals and cost reserve allocations would be revised as needed in future more-detailed studies as appropriate for the specific cost-risks for a given mission concept.

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Executive Summary

The purpose of the Mars 2018 Sky Crane Capabilities Study was to “explore the full range of science capabilities that could be delivered to the surface of Mars in 2018 by an MSL-derived Sky Crane EDL system” [1]. NASA commissioned the Jet Propulsion Laboratory (JPL) to perform this study. The Planetary Science Decadal Survey Mars Panel was particularly interested in the following science pathways: a surface field geology/astrobiology pathway, a subsurface geology/astrobiology pathway, and a network science pathway. There was also an interest in examining mobile and non-mobile options. The key trades in this study involved various combinations of mission elements for the three science pathways and the choice of a mobile versus fixed option. Table ES-1 shows combinations of the mission elements and the four that were selected for detailed study (highlighted in gray).

It is the assessment of the JPL architecture team that all but one of these potential missions are technically feasible (based on technical maturity and mass). Note that the mission with the Mars Astrobiology Explorer-Cacher (MAX-C) Rover, ExoMars Rover, and Network Pathfinder does not meet the required 30% mass margin; however, at this stage of understanding, the 1% margin difference is not sufficient to exclude this option. Further work needs to be done to determine actual feasibility.

In addition to the possible missions, the Mars Panel asked for an investigation on the potential capabilities of the Sky Crane with respect to landing ellipse, landing altitude, and landed mass. Table ES-2 provides a summary of the results of this investigation.

Table ES-1. Potential Missions for Sky Crane Delivery

Pathway Mission	Surface Field Geology / Astrobiology	Subsurface Geology / Astrobiology	Network Science	Comments	Cost ($B FY15)	Sky Crane Delivered Mass / Mass Delivery Margin
Baseline	MAX-C Rover	ExoMars Rover	None	Baseline MAX-C Mission	2.2	992 kg / 35%
Option 2	MAX-C Rover	ExoMars Rover	Network Pathfinder	Adds network to the Baseline Mission	2.4	1,066 kg / 29%
	MAX-C Rover	ExoMars Rover	Network Pathfinder and Seismic Drop Package	Does not fit within Sky Crane capabilities	–	Not feasible
Option 3	MAX-C Rover	None	Network Pathfinder and Seismic Drop Package	Drops subsurface pathway for network science	2.4	801 kg / 47%
	MAX-C Rover	None	Network Pathfinder	Option 3 minus Drop Package	2.4	Not estimated
Option 4	MAX-C Rover	Subsurface Station	Network Pathfinder	–	2.9	933 kg / 38%
	MAX-C Rover	Subsurface Station	Network Pathfinder and Seismic Drop Package	Option 4 plus Drop Package	2.9	Not estimated
	MAX-C Rover	None	None	Cost = Baseline	2.2	Not estimated

Table ES-2. Sky Crane Capabilities

Case	Delivered Mass	Maximum Landing Elevation*	Ellipse Diameter	Notes
MSL in 2018	1,050 kg	-1 km	30 km	N/A
MSL in 2018 w/ improved navigation	1,050 kg	-1 km	22 km	Enhanced attitude and position knowledge
MSL in 2018 w/ position-dependent parachute trigger	1,050 kg	-3 km	15 km	Enhanced capability above, plus position-dependant parachute deployment
MSL in 2018 w/ propulsive-targeting cleanup maneuver	640 kg	-3.5 km	9 km	Capabilities above, plus terrain-relative navigation and propulsive correction (3 km correction)

* Elevation relative to MOLA.

1. Scientific Objectives

1.1 Science Questions and Objectives

The Mars Panel was interested in three science pathways: a surface field geology/astrobiology pathway, a subsurface geology/astrobiology pathway, and a network science pathway. Each of these pathways is described in detail below.

In addition to the pathways, science priorities are identified. Science priorities are a way to trade capabilities within a pathway to enable flexibility in the study. Four levels were defined: the performance floor, below which the mission does not make sense; and good, better, and best levels which each add capabilities above the performance floor. The levels for each pathway were initially provided by the Mars Panel as part of the discussion of how to perform the study and are reproduced here in the discussion of each pathway below.

1.1.1 Surface Field Astrobiology/Geology Pathway

1.1.1.1 Science Questions

The current emphasis of the Mars Exploration Program is on the following questions—has life ever arisen on the planet and what has been the nature and distribution of any habitable environments? Addressing these questions requires that interdisciplinary investigations be conducted at landing sites where habitable conditions might have existed and where conditions also favored the preservation of any evidence of life or prebiotic chemistry. Accordingly, the program must also investigate the geological and geophysical evolution of Mars; the history of its volatiles and climate; the nature of the surface and subsurface environments, now and in the past; the temporal and geographic distribution of liquid water; and the availability of other resources (e.g., energy) necessary to sustain life. Thus, for example, it is necessary to characterize more comprehensively the macroscopic and microscopic fabric of sediments and other materials, reconstruct the history of mineral formation as an indicator of preservation potential and geochemical environments, identify any organic molecules, and determine specific mineral compositions as indicators of coupled redox reactions characteristic of life. These requirements would also guide the selection, caching, and potential return of samples to sophisticated laboratories on Earth. The acquisition and return of martian materials has been a high science priority since the 1970s, and it is a widely held view that Earth-based laboratories would be required to validate discovery of past or extant martian life. The mission described here would be the first in a sequence of missions to locate and return samples in a way that effectively addresses the search for evidence of life on Mars.

1.1.1.2 Science Objectives

The proposed science objectives for a surface field investigation are as follows:

- Land on or rove to a terrain with bedrock exposures that have a high likelihood of providing rock samples that would allow reconstruction of past environmental conditions and provide information about habitability and life.
- Characterize the geological, mineralogical, and compositional contexts of rocks that might be sampled and cached for potential return to Earth.
  - Access multiple sequences of geological units in a search for possible evidence of ancient life and/or prebiotic chemistry.
  - Evaluate the paleoenvironmental conditions of the samples.
  - Characterize their potential to have preserved biological or prebiotic signatures.

- Acquire, package, and preserve a rock core sample cache for potential return to Earth that has a high likelihood of containing information needed to reconstruct past environmental conditions, and information about habitability and life.

1.1.1.3 Driving Requirements

The proposed driving requirements for a surface field investigation are as follows:

- Land on terrain with elevations relative to the MOLA-defined areoid of up to -1 km and within a latitude belt between -15 and 25 degrees with a 3 sigma landing error ellipse of 11 km.
- Drive 20 km to access important geological materials for imaging and spectral characterization using remote sensing instrumentation, followed by contact-based elemental, mineralogical, and textural measurements of natural rock surfaces and interior surfaces exposed by brushing and grinding.
- Acquire 19 primary and 19 contingency rock cores, each 10 gm in mass, for rock targets shown to provide a high likelihood of preserving evidence for past environmental conditions, habitability, and life. Place these cores in primary and contingency caches for retrieval by a possible subsequent mission and fetch rover. (The primary cache should remain with the 2018 rover and the contingency cache should be delivered to a location that would be accessible to a fetch rover.)

1.1.1.4 Science Priorities

The surface field geology/astrobiology pathway included the following *performance-floor* requirements:

- Land in or rove to a terrain with bedrock exposures that have a high likelihood of providing rock samples that would allow reconstruction of past environmental conditions and implications for habitability and life.
- Characterize the geological, mineralogical, and compositional contexts for rock samples collected and cached for potential return to Earth.
- Acquire, package, and preserve a rock core sample cache for potential return to Earth that has a high likelihood of containing the information needed to reconstruct past environmental conditions and implications for habitability and life.

The *good* priority requirement adds:

- Conduct intensive remote sensing and in-situ science campaigns beyond those required for proper selection of rock core samples.

The *better* priority requirement adds:

- Cache soil and atmosphere samples.

The *best* priority requirement adds:

- Mission redundancy.

1.1.2 Subsurface Geology/Astrobiology Pathway

1.1.2.1 Science Questions (Derived from ExoMars Science Questions)

The subsurface geology/astrobiology pathway addresses the following questions: Has life existed on Mars in the past and does it exist today? What is the distribution of water and other chemical compounds as a function of depth in the shallow subsurface? Are there features of the surface environment that might pose hazards to future human missions? How has the planet's subsurface and deep interior contributed to the evolution and habitability of Mars?

1.1.2.2 Science Objectives (Derived from ExoMars Objectives)

The proposed science objectives for a subsurface field investigation are as follows:

- Travel several kilometers to sites where records of recent climate, geologic processes, and organic molecules might be well preserved and accessible in the near subsurface.
- Perform visible and infrared observations to characterize the local terrain and measure atmospheric gases that may indicate biological activity.
- Utilize a drill to collect soil and rock samples from the subsurface to a depth of 2 meters.
- Analyze subsurface samples using a color microscopic imager, an organic molecule analyzer, and spectroscopic analyzers to identify minerals.

> *The proposed suite of ExoMars Rover-based analytical instruments…are included here to provide examples of the measurements envisioned to support exobiology and geology research. A* ***Pancam*** *instrument would include a Wide Angle Camera for multi-spectral stereoscopic panoramic imaging and a High Resolution Camera for high-resolution color imaging. The* ***Water Ice and Subsurface Deposit Information on Mars (WISDOM)*** *would be a ground penetrating radar (GPR) operating in the UHF frequency range from about 500 MHz to 3 GHz. Its radar should penetrate 2 to 3 meters, similar to the depth reached by the Rover drill system for sample acquisition. The* ***Mars Multispectral Imager for Subsurface Studies (MA_MISS)*** *is an infrared spectrometer that would be located in the drill and conduct mineralogical studies. The* ***Raman/Laser-Induced Breakdown Spectroscopy (Raman/LIBS)*** *instrument would identify minerals and organic compounds in samples acquired by the drill.* ***MicrOmega*** *would be a visible / IR microscope designed to examine the collected samples to characterize their structure and composition at grain size level. The* ***Mars X-ray Diffractometer (Mars-XRD)*** *would use a radioisotope source to irradiate powdered rock samples to identify minerals. The* ***Mars Organic Molecule Analyser (MOMA)*** *instrument would identify molecular species at low concentrations (that is ppb to ppt) and with high analytic specificity.* [2]

1.1.2.3 Driving Requirements

The proposed driving requirements for a subsurface field investigation are as follows:

- Land on terrain with elevations relative to the MOLA-defined areoid of up to -1 km and within a latitude belt between -15 and 25 degrees with a 3 sigma landing error ellipse of 11 km.
- Drive several km to access important geological materials for imaging and spectral characterization using remote sensing instrumentation, followed by elemental, mineralogical, textural, and organic measurements of rock and soil samples obtained by the 2 m drill.
- Acquire subsurface drill samples, each 10 gm in mass, for rock targets shown to provide a high likelihood of preserving evidence for past environmental conditions, habitability, and perhaps life. Place these cores in a cache for retrieval by a potential subsequent mission and fetch rover.

1.1.2.4 Science Priorities

The subsurface geology/astrobiology pathway initially included two paths: a sample return path and an in-situ analysis path. Both paths are represented in the requirements below:

The *performance-floor* and *good* priority requirements are as follows (same requirements for both):

- Acquire, package, and preserve a core sample cache for potential return to Earth that has a moderate likelihood of containing the information needed to address past or present life questions.
- Acquire core samples for in-situ analysis that have a moderate likelihood of containing the information needed to address past or present life questions.

The *better* priority requirement adds:

- Acquire core samples for in-situ analysis that have a high likelihood of containing the information needed to address past or present life questions. Scientifically select appropriate samples to package and preserve within a sample cache for potential return to Earth.

The *best* priority requirement adds:

- Above, plus (1) increased sophistication of in-situ analysis, (2) consideration of increased mobility for sample diversity, and (3) maintenance of samples at temperature conducive to life investigations.

1.1.3 Network Science Pathway

1.1.3.1 Science Questions

The network science pathway addresses the following questions:

How has the planet's subsurface and deep interior contributed to the evolution and habitability of Mars?

What is the structure and thickness of the lithosphere beneath the landing site? The present volcanic, tectonic and interior structure of Mars is poorly understood. Only gravity and geodetic data have constrained the interior structure. A network of seismology stations could address these and other key questions.

How do atmosphere-ground interactions and atmospheric structure and dynamics determine martian weather and climate? Frequent meteorological measurements must be conducted simultaneously at multiple locations, preferably for several martian years.

What is the nature of any subsurface water-related structures? The recent discovery of methane in the atmosphere opens the question of the present heat flow and therefore the depth of possible liquid water and degree of internal activity. Geophysical measurements could map subsurface water-related structures.

How have volcanism and other tectonic processes affected the development of the crust and mantle? Heat flow from the martian interior has been a key driver of such processes yet our current estimates of martian heat flow derive principally from theoretical models.

How has the martian magnetic field varied over time? Remnant magnetism of crustal rocks can record the history of the local magnetic field. The identification of magnetized rocks also might be the best way to identify and sample rocks from the oldest period of Mars, as the dynamo is expected to have stopped earlier than 500 million years after planet formation.

1.1.3.2 Science Objectives

The proposed science objectives for a network field investigation are provided below.

The primary objectives are as follows:

- Utilize seismology to measure the structure and thickness of the lithosphere beneath the landing site for at least 1.5 Earth years.
- Provide a meteorology survey of the landing site for at least 1.5 Earth years.

The secondary objectives (in priority order) are as follows:

- Determine the heat flow of the landing site.
- Map any subsurface water-related structures and layering.
- Validate the measurement strategy for a multi-station seismology network by conducting seismology measurements for at least 2 martian years.

- Determine the lithosphere and upper mantle structure below the landing site.
- Assist the mission in the identification of magnetized rocks.

1.1.3.3 Driving Requirements

The proposed driving requirements for a network field investigation are provided below.

The primary requirements are as follows:

- Land on terrain with elevations relative to the MOLA-defined areoid of up to -1 km and within a latitude belt between -15 and 25 degrees with a 3 sigma landing error ellipse of 11 km.
- Provide a "live" lander station on the pallet with avionics designed to operate for a minimum of 1.5 Earth years.
- Deliver and operate a seismology instrument for a minimum of 1.5 Earth years.
- Deliver and operate a meteorology station for a minimum of 1.5 Earth years.

The secondary requirements (in priority order) are as follows:

- Deliver and operate a heat-flow mole system for a minimum of 1.5 Earth years.
- Deliver and operate an electromagnetic (EM) sounding experiment to map any subsurface water-related structures.
- Extend the lifetime of the seismometer to 2 martian years, if a network mission is planned to launch during the following launch window.
- Deliver and operate a diagnostic magnetometer on the caching rover.

1.1.3.4 Science Priorities

The network science pathway included the following *performance-floor* requirements:

- Provide the crustal thickness and the crustal layering of the landing site.
- Provide a meteorological survey of the landing site.

The *good* priority requirement adds:

- Determine the heat flow on the landing site.
- Identify magnetized rocks.
- Map subsurface water-related structures and layering.

The *better* priority requirement adds:

- Determine the lithosphere and upper mantle structure below the landing site.

The *best* priority requirement adds:

- Prepare for a future network mission.

1.2 Science Traceability

Science traceability matrices for each of the three pathways are provided below in Tables 1-1, 1-2, and 1-3.

Table 1-1. Surface Field Astrobiology/Geology Pathway Traceability Matrix

Science Objective	Measurement	Instrument	Functional Requirement
Land on or rove to a terrain with bedrock exposures that have a high likelihood of providing rock samples that would allow reconstruction of past environmental conditions and provide information about habitability and life.	Land on terrain with elevations relative to the MOLA-defined areoid of up to -1 km and within a latitude belt between -15 and 25 degrees with a 3 sigma landing error ellipse of 11 km.	–	MSL Sky Crane landing system
	Drive 20 km to access important geological materials	–	Rover with 20 km range
Characterize the geological, mineralogical, and compositional contexts of rocks that might be sampled and cached for potential return to Earth. • Access multiple sequences of geological units in a search for possible evidence of ancient life and/or prebiotic chemistry. • Evaluate the paleoenvironmental conditions of the samples. • Characterize their potential to have preserved biological or prebiotic signatures.	Geological context imaging at the field scale	Pancam	Mast on rover
	Mineralogical context at the field scale	NIR point spectrometer	Mast on rover
	Mineralogical context at the microscopic scale	Raman spectrometer	Arm to deploy and support
	Compositional context	APXS	Arm to deploy and support
	Geological context imaging at the microscopic scale	Microscopic imager	Arm to deploy and support
Acquire, package, and preserve a rock core sample cache for potential return to Earth that has a high likelihood of containing information needed to reconstruct past environmental conditions, and information about habitability and life.	Acquire 19 primary and 19 contingency rocks cores, each 10 gm in mass. Place these cores in primary and contingency caches for potential retrieval by subsequent mission.	Corer/abrader Cache sample handling and container	Arm to support corer

Table 1-2. Subsurface Astrobiology/Geology Pathway Traceability Matrix

Science Objective	Measurement	Instrument	Functional Requirement
Travel several kilometers to sites where records of recent climate, geologic processes, and organic molecules might be well preserved and accessible in the near subsurface.	Land on terrain with elevations relative to the MOLA-defined areoid of up to -1 km and within a latitude belt between -15 and 25 degrees with a 3 sigma landing error ellipse of 11 km.	–	MSL Sky Crane landing system
	Drive to access important geological materials for imaging and spectral characterization	–	Rover with several km range
Perform visible and infrared observations to characterize the local terrain and measure atmospheric gases that may indicate biological activity.	Visible observations	Panoramic camera	Mast
	Infrared observations	Infrared imaging spectrometer	Mast
	Measure atmospheric gases	Gas chromatography mass spectrometry	–
Utilize a drill to collect soil and rock samples from the subsurface to a depth of 2 meters.	–	2 meter drill	Stable drilling platform
Analyze subsurface samples using a color microscopic imager, an organic molecule analyzer, and spectroscopic analyzers to identify minerals.	Color microscopic imaging	Multispectral imager	–
	Organic molecule analysis	Gas chromatography mass spectrometer	–
	Mineral identification	X-ray diffractometer	Sample handling
Acquire, package, and preserve a rock core sample cache for potential return to Earth that has a high likelihood of containing information needed to reconstruct past environmental conditions, and information about habitability and life.	Acquire subsurface drill samples, each 10 gm in mass, for rock targets shown to provide a high likelihood of preserving evidence for past environmental conditions, habitability, and perhaps life. Place these cores in a cache for potential retrieval by subsequent mission and fetch rover.	2 meter drill Cache sample handling and container	Sample handling

Table 1-3. Network Science Pathway Traceability Matrix

Science Objective		Measurement	Instrument	Functional Requirement
1.	Provide geological context of the site	Seismic	3-axis seismometer	–
	Provide crustal thickness and layering	Seismic	3-axis seismometer	–
	Provide meteorological survey	Temperature, pressure, humidity, wind, dust	Meteorological sensors on a boom	–
2.	Determine heat flow	Heat flow	Mole with heat flow probe	–
	Identify magnetized rocks	Magnetics	Magnetometer	–
	Map subsurface volatiles	EM sounding	EM sounder	–
3.	Determine lithosphere and upper mantle structure at landing site	Seismic at two locations 10 to 20 km apart	3-axis seismometer plus 1-axis seismometer	Seismic drop package
4.	Begin a martian geophysical network	Seismic and meteorological measurements	Long-lived 3-axis seismometer and meteorological stations	> 2 martian year lifetime

2. High-Level Mission Concept

2.1 Overview

The purpose of this study was to "explore the full range of science capabilities that could be delivered to the surface of Mars in 2018 by a MSL-derived Sky Crane EDL system" [1]. The Mars Panel was interested in the following science pathways: a surface field geology/astrobiology pathway, a subsurface geology/astrobiology pathway, and a network science pathway. There was also an interest in examining mobile and non-mobile options for each of these pathways, with particular interest in missions that addressed all three pathways.

The science champion and his team provided draft science objectives for the three science pathways. These objectives included four levels of prioritization: *performance floor*, *good*, *better*, and *best* (see Section 1). Strawman implementations, including science payloads, were also provided for each priority level and pathway.

The JPL architecture team completed an initial assessment of more than a dozen potential design elements, with the potential combinations of these elements being very large. The JPL architecture team made recommendations to the science champions on what study elements would best address the trade space and answer the questions from the Mars Panel. The agreed-upon elements were then studied through Team X point designs. The study team then assessed the various combinations of elements requested by the Mars Panel.

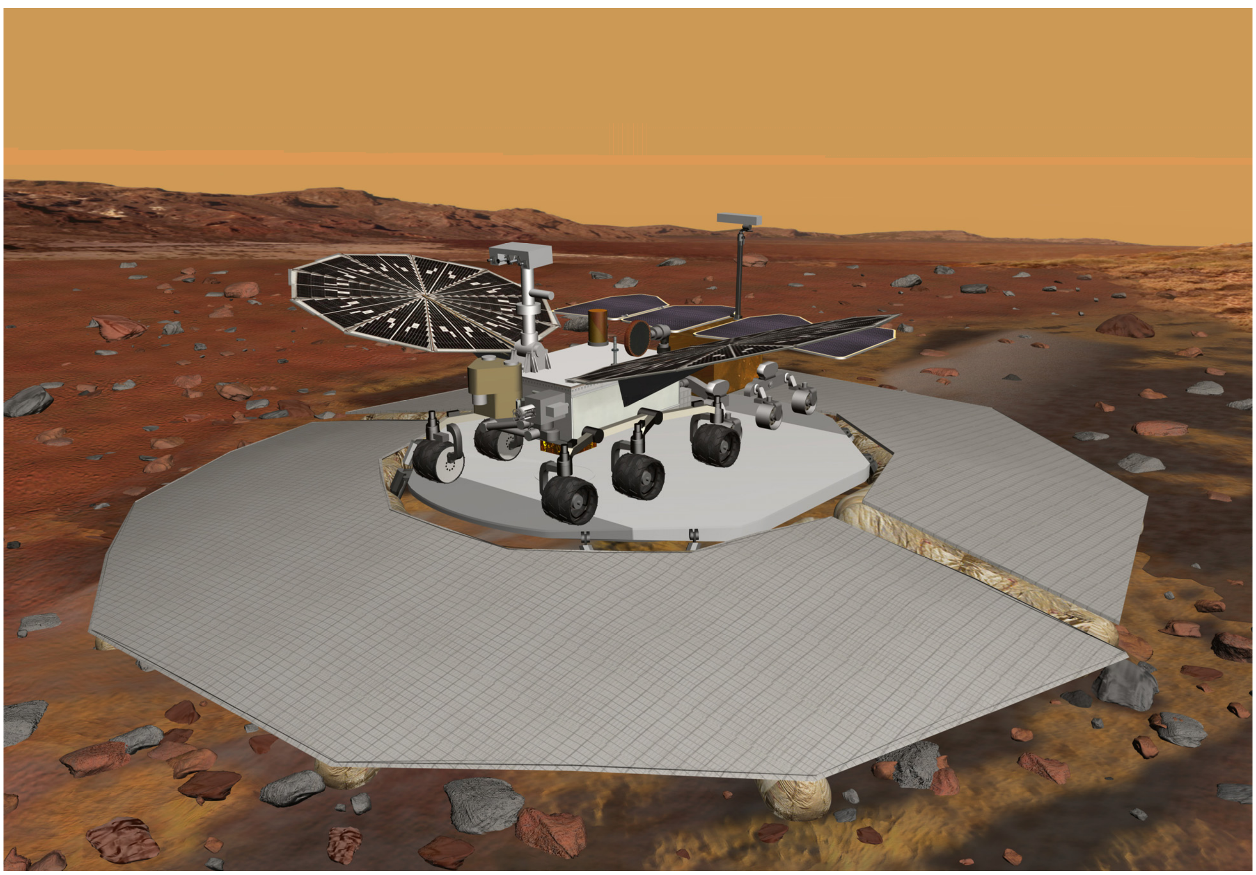

Figure 2-1. Artist's Conception of the Proposed MAX-C and ExoMars Rovers on the Landing Pallet

All study architectures assumed a Mars Science Laboratory (MSL)-derived Sky Crane descent system to deliver the science payloads to the surface. The main trades for the study are the sets of science payload that could be delivered by the Sky Crane in the 2018 Mars opportunity.

In addition to the science packages, the study examined delivery capabilities for the Sky Crane system in the 2018 opportunity.

2.2 Concept Maturity Level

Table 2-1 summarizes the NASA definitions for concept maturity levels (CMLs). Products of this study range from CML 3 to CML 4. Point designs were completed on certain elements of the architecture in order to explore trade space architectures.

Table 2-1. Concept Maturity Level Definitions

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, V&V approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

2.3 Science Pathway Implementation

The selected priorities for study and the reasons for selecting them for each of the three science pathways are discussed below.

Surface Field Astrobiology/Geology Pathway. Discussion among the full study team determined that the proposed MAX-C Rover, under analysis in another Mars Panel study, met the requirements of both the *performance-floor* and the *good* priority level. The Mars Panel was not interested in a fixed geology package, due to the strong desire to be able to access the appropriate rocks of for caching. The JPL team recommended, based on significant past work on the proposed Mars Sample Return (MSR), that the caching of soil and atmosphere samples not be carried on the sample return lander. Mission redundancy is easily determined as part of any mission study. Thus, the proposed MAX-C Rover was selected as the mission element for the surface field geology/astrobiology pathway. Details of the MAX-C Rover can be found in the MAX-C mission concept study report [3].

Subsurface Geology/Astrobiology Pathway. Discussion among the study team determined that the European Space Agency (ESA) ExoMars Rover, currently under development and also under discussion for delivery to Mars with the proposed MAX-C Rover in the 2018 opportunity, would meet the *performance-floor* and *good* priority requirements for the mobile element of the astrobiology pathway. To further explore the trade space, and in case the ExoMars discussions do not come to fruition, a fixed Subsurface Station that would meet the *better* priority requirements was selected as an additional mission element to study.

Network Science Pathway. Due to the strong desire to have one mission implementation including all three pathways, the first element for this pathway would be the Network Pathfinder, which would meet the *performance-floor* requirements. A Seismic Drop Station, consisting of a seismometer that could be

operated in conjunction with the Network Pathfinder, and would address the *better* priority requirement, was also studied to examine a mobile element for the network science pathway. Note that in either case, the *good* priority objectives are not addressed.

2.4 Mass Delivery Capabilities of the MSL-Derived Sky Crane

The delivery capabilities of an MSL-derived EDL/Sky Crane system for the 2018 opportunity have been estimated by applying the current understanding of the system's sensitivities and adjusting for conditions expected in the 2018 arrival season. Additionally, the performance impact of several options for improving landed precision has been estimated based on landing precision studies commissioned by the Mars Program in fiscal year (FY) 2009. The options and their impact on performance are described below.

The 2018 opportunity would afford a more favorable part of the seasonal pressure cycle for landed mass than MSL's 2011 opportunity; however, the increased risk of exposure to dust events would partially offset the increased mass capability and also negatively impact landing precision. As shown in Table 2-2, after accounting for the positive and negative atmosphere impacts, the delivery mass capability is estimated to be 1,050 kg, roughly 100 kg more than MSL. Dust impact on wind fields would cause additional variability in the amount and direction of wind drift experienced while on parachute. This would result in an increase to the landing ellipse diameter to 30 km versus MSL's 25 km ellipse.

Several options for improving landing precision have been considered. Improving navigated state knowledge at entry, through improved attitude initialization knowledge and through either spacecraft to spacecraft navigation or optical navigation, would improve expected landing precision. The improved state knowledge would enable guided entry to be more accurate in controlling range to target; this would result in an estimated 22 km landing ellipse.

Adding a range-based parachute deployment trigger, rather than a simple velocity trigger, to the enhanced state knowledge approach could further increase landing precision. Often dubbed "smart chute," this option would deploy the supersonic parachute when the desired range flown has been met, resulting in significant precision improvement. Unfortunately, this option would come at the expense of landing elevation capability, because parachute deployment must be delayed from the maximum allowable inflation Mach to allow flexibility to deploy using range information. The landing elevation expense would depend on the atmospheric conditions and correlations for a given landing site, but could be estimated at approximately 2 km for most cases. The improved ellipse for the 2018 opportunity is estimated at 15 km in diameter.

Table 2-2. Sky Crane Capabilities

Case	Delivered Mass	Maximum Landing Elevation*	Ellipse Diameter	Notes
MSL in 2018	1,050 kg	-1 km	30 km	N/A
MSL in 2018 w/ improved navigation	1,050 kg	-1 km	22 km	Enhanced attitude and position knowledge
MSL in 2018 w/ position-dependent parachute trigger	1,050 kg	-3 km	15 km	Enhanced capability above, plus position dependant parachute deployment
MSL in 2018 w/ propulsive-targeting cleanup maneuver	640 kg	-3.5 km	9 km	Capabilities above, plus terrain-relative navigation and propulsive correction (3 km correction)

* Elevation relative to MOLA.

The final precision enhancement considered would add a propulsive correction of approximately 3 km to the improvements discussed above (enhanced knowledge and range based parachute triggering). This option elects to sacrifice delivery mass for additional propellant and associated hardware. The system would then use the additional propellant to fly up to 3 km toward a desired landing target, resulting in a 9 km ellipse diameter.

2.5 High-Level Description of Study Elements

This study examined both mobile and non-mobile options. Table 2-3 provides the selection of mission elements across these two trade space axes.

The fixed surface field geology/astrobiology pathway was not considered a viable option based on the experiences with the Mars Exploration Rover (MER). Each mission element is described in detail in Section 3 of this report or in the MAX-C mission concept study report [3].

Table 2-3. Trade Space Assignment of Mission Element to Science Pathways

Science Pathway	Mobile Option	Fixed Option
Surface field geology/astrobiology	MAX-C Rover	Not studied
Subsurface geology/astrobiology	ExoMars Rover	Subsurface Station
Network science	Network Pathfinder and Seismic Drop Package	Network Pathfinder

2.6 Technology Maturity

Each of the point designs used MSL or technologies being developed for the proposed MAX-C, with the possible exception of two areas: planetary protection for the Subsurface Station and payload/instrumentation. Planetary protection for the drilling and sample handling was identified as an area of potential concern, but an assessment for what it would take to mitigate this was not analyzed or costed. The instrument payloads assumed are representative of the instrumentation that would be needed. However, specific instrumentation for the missions awaits more detailed science planning; as such, there is the potential that instrument technology development might be needed. This was not assessed or costed.

3. Technical Overview

3.1 Introduction

This section provides a description of the individual mission elements studied and the four missions generated from these elements.

3.1.1 Redundancy Approach

The current baseline reliability approach for the missions studied in this report uses “selective redundancy” as implemented for Spirit and Opportunity. This is consistent with the mission duration of less than one Mars year on the surface of Mars and the restricted latitude range that would avoid many of the extreme thermal environments between latitudes of ±45 degrees for which the fully redundant MSL was designed. The extent of the selective redundancy is one of the major trade studies to be considered during the project's pre-Phase A and Phase A studies, and will be formally documented prior to the mission PDR.

3.2 Mission Elements

3.2.1 MAX-C Rover

The proposed MAX-C element would be a MER-class rover and is described in detail in the MAX-C mission concept study report [3]. The rover (Figure 3-1) would include a MER-like mobility system capable of roving outside the landing ellipse (~20 km roving distance). The rover would be required to survive at least 500 sols (~514 days or ~1.5 Earth years) on the martian surface. Mast-mounted stereo imaging and spectroscopic instruments would provide MER-like capabilities for mobility, terrain, and material property characterization. The arm would contain MER-like capabilities (such as MB, APXS, MI, and RAT), which would allow contact measurements of texture, mineralogy, and composition for surface and subsurface beneath dust and thin (<several mm) coatings. Additional capability beyond MER would include the ability to collect and cache thirty 10 gm rock cores from five separate locations with bit changes as needed and separate encapsulating sleeves for core samples; and the inclusion of a Raman spectrometer or other instrument to detect mineralogy and organic materials and micro-mapping of mineralogy, composition, and texture for natural and prepared surfaces. See the MAX-C mission concept study report for additional details [3].

3.2.1.1 Instrument Payload Description

The projected MAX-C payload (Table 3-1) consists of a complementary set of five optical and spectrometry instruments that would be used to select and analyze samples to understand past environmental conditions and the probability of conditions for habitability. The most interesting samples would be stored in a primary and backup sample cache that would be returned at a later date by the proposed MSR Mission. The projected payload represents a mix of already flown instruments (Pancam, APXS, and MI) and newer technologies (NIR-point spectrometer, Raman spectrometer).

3.2.1.2 Flight System

Table 3-2 provides the preliminary estimates for flight system subsystem masses, subsystem power in each operational mode, total mass and power, and margins.

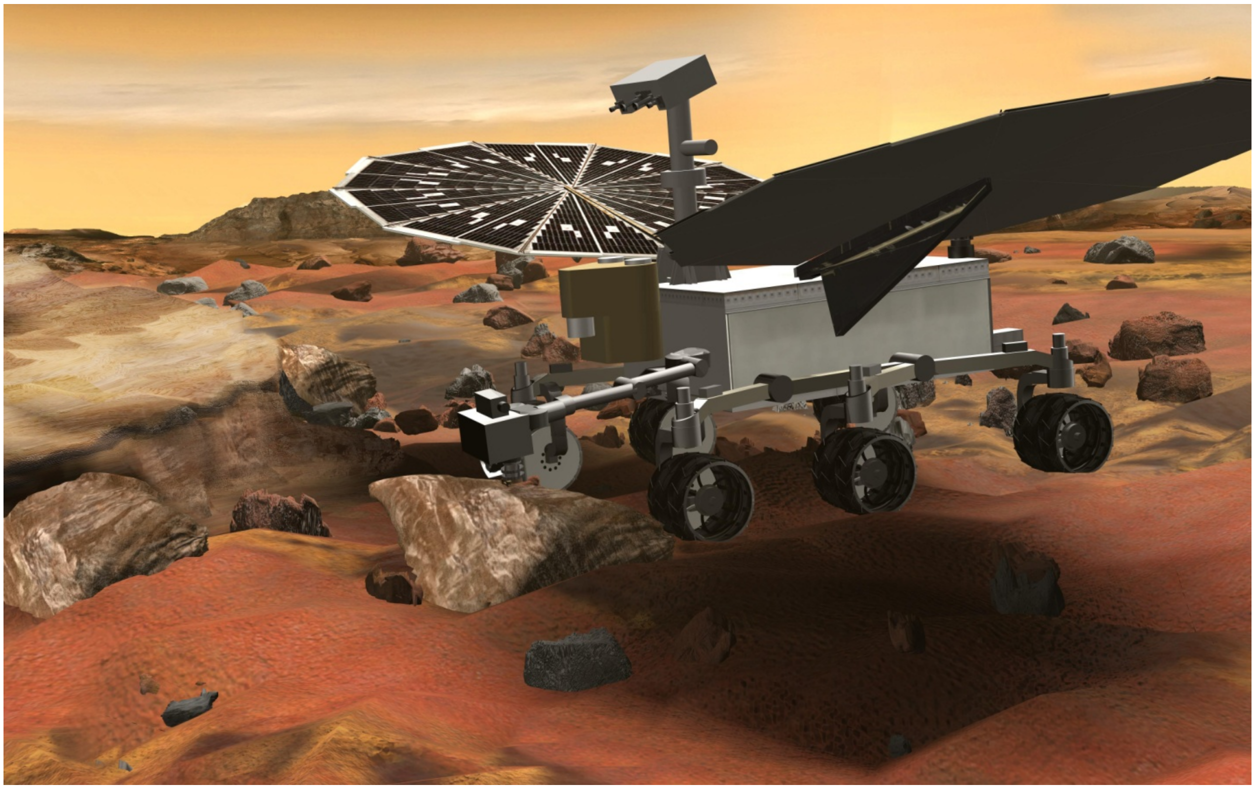

Figure 3-1. Artist's Conception of the Proposed MAX-C Rover

Table 3-1. MAX-C Payload Mass and Power Preliminary Estimates

	Mass			Op. Power			Data Rate^
	CBE (kg)	Cont. %	MEV (kg)	CBE (W)	Cont. %	MEV (W)	CBE (kbps)
Pancam	1.2	30%	1.6	3	30%	4	2,400
NIR-point spectrometer	3.5	30%	4.6	12	30%	16	2,400
Raman spectrometer	5	30%	6.5	25	30%	33	100
APXS	1.7	30%	2.2	10	30%	13	18
Microscopic imager	0.3	30%	0.4	10	30%	13	2,400
Mast	7.7	30%	10	8	30%	10	1
Cache sample handling and container	9	30%	11.7	10	30%	13	1
Arm => short, low pre-load	10.3	30%	13.4	20	30%	26	1
Organic blank	1.5	30%	2	2	30%	3	0
Corer/abrader	5	30%	6.5	75	30%	98	1
Total Payload Mass	**45.2**	**30%**	**58.8**	**–**	**–**	**–**	**–**

^Instrument data rate defined as science data rate prior to on-board processing

Note: See Flight System mass and power table for average power use in each operational mode.

Table 3-2. MAX-C Rover Mass and Power Preliminary Estimates

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Autonomous Roving	Mode 2 Power (W) Mast Science	Mode 3 Power (W) Arm Science	Mode 4 Power (W) Analysis (Rover Off)	Mode 5 Power (W) Coring	Mode 6 Power (W) Telecom Relay (UHF)	Mode 7 Power (W) Standby w/ Telecom HGA Uplink	Mode 8 Power (W) Sleep (Rover Off)	Mode 9 Power (W) Actuator Warm-up (Rover Off)	Mode 10 Power (W) Sample Tool Manipulation
Power Mode Duration (hours)					*0.25*	*0.25*	*5*	*12*	*3*	*0.2*	*0.5*	*13.3*	*1*	*1*
Payload on this Element														
Instruments	18%	45.2	30%	58.8	0	13	30	0	78	0	0	0	0	14
Payload Total	18%	**45.2**	30%	**58.8**	**0**	**13**	**30**	**0**	**78**	**0**	**0**	**0**	**0**	**14**
Spacecraft Bus			do not edit formulas below this line, use the calcualtions and override tables instead -->											
Attitude Control	3%	7.5	22%	9.1	46	4	10	0	4	0	4	0	0	10
Command & Data	5%	12.5	7%	13.4	53	53	53	53	53	53	53	12	0	0
Power	16%	41.9	30%	54.5	27	22	24	20	27	26	22	14	25	15
Structures & Mechanisms	37%	94.5	30%	122.8	0	0	0	0	0	0	0	0	0	0
Cabling	8%	21.3	30%	27.7										
Telecom	6%	15.1	7%	16.2	0	0	0	0	0	70	13	0	0	0
Thermal	7%	16.9	19%	20.2	3	3	3	3	3	3	3	3	163	3
Bus Total		209.7	26%	263.9	128	81	89	75	86	151	94	28	188	27
Thermally Controlled Mass				263.9										
Spacecraft Total (Dry)		254.9	27%	322.6	128	94	120	75	164	151	94	28	188	41
Subsystem Heritage Contingency		67.7	27%	27%										
System Contingency		41.9	16%	16%	55	40	51	32	70	65	40	12	81	18
Spacecraft with Contingency		**365**	of total	w/o addl pld	**183**	**134**	**171**	**108**	**234**	**216**	**134**	**40**	**269**	**58**
Spacecraft Total (Wet)		**365**												

Structure. The proposed MAX-C Rover would be approximately 50% larger than the MER rover and would be powered by two Ultraflex solar arrays. MAX-C would travels on a wheelbase of approximately 1.7 m by 1.6 m providing a ground clearance of approximately 0.35 m. The rover chassis preliminary design is 1.1 m in length, 0.75 m wide, and 0.46 m tall and would support a forward mounted robotic arm supporting a dual Raman spectrometer head, an APXS head, and a microscopic imager head. Also a dual-canister sample handling, encapsulation, and containerization (SHEC) would be installed on the forward panel. An instrument mast used to mount a Pancam and NIR spot/line spectrometer head would be attached to the top deck of the chassis.

Thermal Control. The proposed MAX-C Rover thermal design would benefit from extensive heritage from Pathfinder, MER, and MSL. The rover must be able to withstand temperatures from -40°C to +50°C. The warm electronics box (WEB) and the instrument complement would be smaller than on MSL. The WEB and the battery assembly would employ MSL-heritage CO_2 insulation. RHUs are baselined for thermal control as they were in MER, with additional electrical heaters for warm-up and remote locations. The solar arrays would be used as shunt radiators.

Telecom. The proposed MAX-C Rover would support a two-way link with Earth through all phases of the mission, consisting of direct-to-Earth (DTE) communications via X-band and at UHF via a relay orbiter. The system design has high heritage from MSL except that the UHF subsystem would be a single-string design. The system would employ one 2-axis gimbaled 0.28 m high gain antenna (HGA) for primary communications and one X-band low gain antenna (LGA) as required. The system would use one small deep space transponder (SDST) for X-band communications and one UHF Electra Lite. It is expected that the relay assets would provide two passes of at least 5 minutes each sol.

Attitude Control. The proposed rover would have a single IMU used for 3-axis attitude measurement during deployment. Forty-two distributed drive controllers and actuators would be used to perform various functions of the rover, including speed and HGA gimbal control. Four hazard cameras and two navigation cameras would be provided to support driving and arm operations.

Command & Data Handling. The proposed MAX-C Rover avionics would use the JPL MSAP system with a new avionics development for the distributed motor controller system. Unlike MSL, the MAX-C Rover would employ a single-string design. The avionics system would include RAD750, a critical relay control card (CRCC), a non-volatile memory and camera card (NVMCAM), a telecom interface card (MTIF), serial interface assembly (MSIA), remote engineering units (REU), and power converters. The data storage of 4 Gbits (on the NVMCAM) should be able to support the science mission with ample margin. A maximum data collection rate of 270 Mbits/sol was assumed. The avionics design is shown in Figure 3-2.

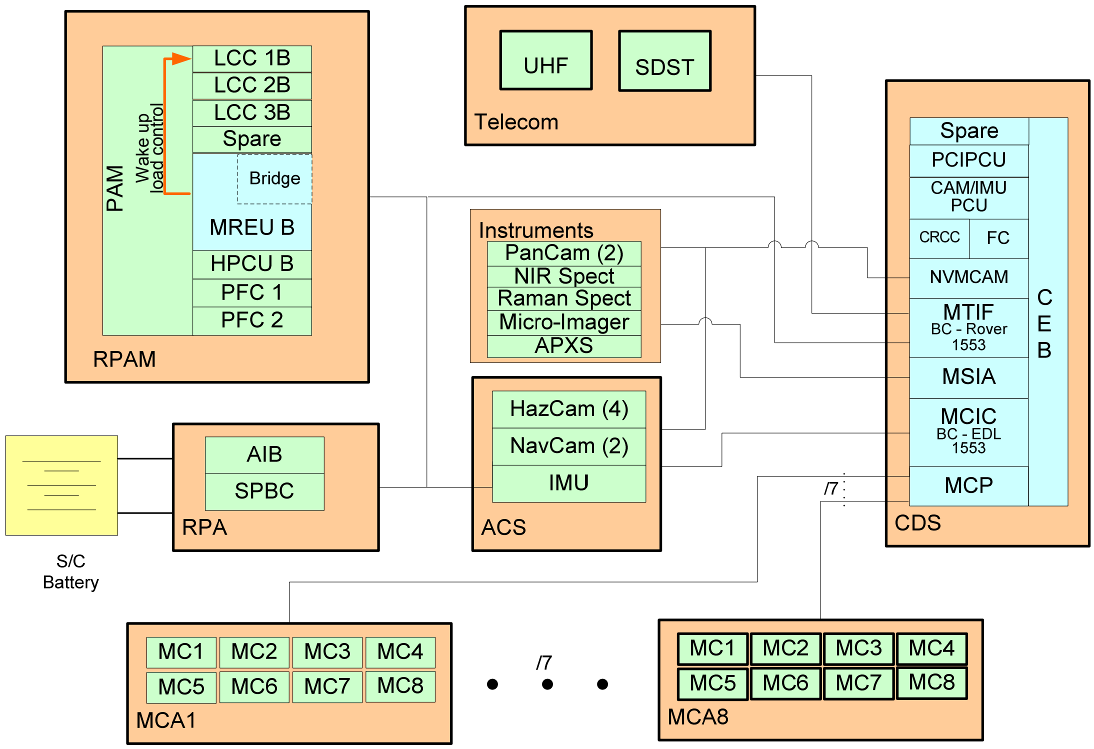

Figure 3-2. Proposed MAX-C Rover Avionics Design

Power. The power subsystem for the proposed MAX-C Rover would consist of two Ultraflex solar arrays at a total area of 6.03 m^2 and a single battery using small cell Li-ion technology in a single 30 A-Hr module. The mission would require approximately 1,600 W-hrs/sol during surface operations, with a lifetime of 500 sols. The design assumed an atmospheric opacity (tau) of 0.5 and a dust accumulation rate of 10% per 100 sols (consistent with MER observations). The design examined the solar availability at 25 N and 15 S latitude over the course of 18 months and was sized for the worst case. The proposed MAX-C Rover would utilize MSAP architecture for the electronics, which has MSL heritage.

3.2.2 ExoMars

The ExoMars element is the ESA rover currently under development. For this study, it was given a mass allocation of 300 kg, including contingency.

3.2.3 Network Pathfinder

The proposed Network Pathfinder would be a fixed scientific package with two instruments. It would be mounted on the landing pallet, which would deliver it to the martian surface on a Sky Crane entry system. The Network Pathfinder would be solar-powered, with a design life of 18 months on the surface. The system is a single-string design and carries 43% mass and power contingencies.

3.2.3.1 Instrument Payload Description

The Network Pathfinder would have two science instruments (Table 3-3). A three-axis seismometer that would measure tectonic movements and a meteorological package (MET) that would include a wind sensor (speed and direction), several temperature sensors, and tunable diode lasers (TDL), which would measure water vapor amounts and specific isotopes of water and carbon dioxide. Pressure sensors would be mounted within the Network Pathfinder.

Table 3-3. Network Pathfinder Payload Mass and Power Preliminary Estimates

	Mass			Average Power			Data Rate^		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)	CBE (kbps)	% Cont.	MEV (kbps)
Seismometer (3-axis)	7.5	30%	9.75	3	30%	3.9	10	30%	13
Meteorological package	2.5	30%	3.25	2	30%	2.6	3	30%	4
Total Payload	**10**	**30%**	**13**	**5**	**30%**	**6.5**	**13**	**30%**	**17**

^Instrument data rate defined as science data rate prior to on-board processing.

3.2.3.2 Flight System

Table 3-4 provides the preliminary estimates for flight system subsystem masses, subsystem power in each operational mode, total mass and power, and margins.

Structure. The proposed Network Pathfinder would have a simple structure necessary for supporting telecom, power, and thermal hardware. The resulting design was scoped as a simple enclosure structure. Solar array area for the Network Pathfinder would be acquired using the top deck of the landing pallet.

Thermal Control. The thermal control for the proposed Network Pathfinder baseline includes thermal insulation and one RHU. Thermal insulation, which would be similar to MSL thermal insulation and has a mass density similar to MLI, would use the MLI layers to minimize thermal convection so that the insulation properties of the martian atmosphere, which is CO_2 at a pressure of ~8 torr, would be maximized. The Network Pathfinder would be mounted on the pallet; with the pallet thermal control, the use of CO_2 insulation, and the RHU, the Network Pathfinder would be maintained within operational limits.

Telecom. The proposed Network Pathfinder would have its own ultra-high frequency (UHF) telecom system for communicating with an orbiting Mars asset. It would carry an Electra Lite UHF transponder and a UHF quad-helix antenna, which are identical to those on the proposed MAX-C Rover. No new hardware would be required for the Network Pathfinder.

Table 3-4. Network Pathfinder Mass and Power Preliminary Estimates

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Science during day	Mode 2 Power (W) Science with telecom	Mode 3 Power (W) Safe	Mode 4 Power (W) Night
Power Mode Duration (hours per sol)					*10.4333*	*0.16667*	*24.6*	*14*
Payload on this Element								
Instruments	24%	10.0	30%	13.0	5	5	0	5
Payload Total	24%	**10.0**	30%	**13.0**	**5**	**5**	**0**	**5**
Spacecraft Bus			do not edit formulas below this line, use the calcualtions and override tables ins					
Attitude Control	0%	0.0	0%	0.0	0	0	0	0
Command & Data	9%	3.7	30%	4.8	2	8	2	2
Power	34%	14.1	30%	18.4	3	9	3	3
Propulsion1	0%	0.0	0%	0.0	0	0	0	0
Structures & Mechanisms	12%	4.8	30%	6.3	0	0	0	0
S/C-Side Adapter	0%	0.0	30%	0.0				
Cabling	8%	3.1	30%	4.0				
Telecom	9%	3.6	3%	3.7	0	70	0	0
Thermal	4%	1.7	0%	1.7	2	2	2	2
Bus Total		31.0	25%	38.9	6	89	6	6
Thermally Controlled Mass				38.9				
Spacecraft Total (Dry)		41.0	26%	51.9	10	94	6	10
Subsystem Heritage Contingency		10.8	26%	26%				
System Contingency		6.8	17%	17%	5	40	3	5
Spacecraft with Contingency		**59**	of total	w/o addl pld	**15**	**134**	**9**	**15**
Spacecraft Total (Wet)		**59**						

Command & Data Handling. The proposed Network Pathfinder would have interfaces with the Electra-telecom interface, a seismometer, and a meteorological station. Since the instruments could take and store data without involving the avionics, a custom SPARC processor board and an event-timer module/instrument-interface card would maximize functionality and flexibility while preserving power and mass margins.

The avionics would only be required to manage telecom data transfer. The event timer module (ETM) would have an always-powered domain and would be responsible for waking up the SPARC processor to manage data transfer from instruments to the Electra-radio. The "sometimes-powered" domain of the ETM board would include a field-programmable gate array (FPGA) to help configure the instrument interfaces and manage data transfer.

Figure 3-3 shows the avionics design for both the proposed Network Pathfinder and Seismic Drop Package.

Power. The proposed Network Pathfinder's power subsystem would consist of a rigid 1.49 m^2 TJ GaAs solar array, an 18 A-hr Li ion battery and electronics (array switch card and a custom ETM). The solar array was sized to provide 395 W-hrs per sol at end of life (EOL) (18 months) to support the science and telecom operations during the day and battery recharge. The design assumed an atmospheric opacity (tau) of 0.5 and a dust accumulation rate of 10% per 100 sols (consistent with MER observations). The design examined the solar availability at 25 N and 15 S latitude over the course of 18 months and was sized for the worst case. The battery was sized to support nighttime instrument operations with a maximum depth of discharge of 37%. The custom ETM would be a new development for this mission, but the rest of the power subsystem would have MER and MSL heritage.

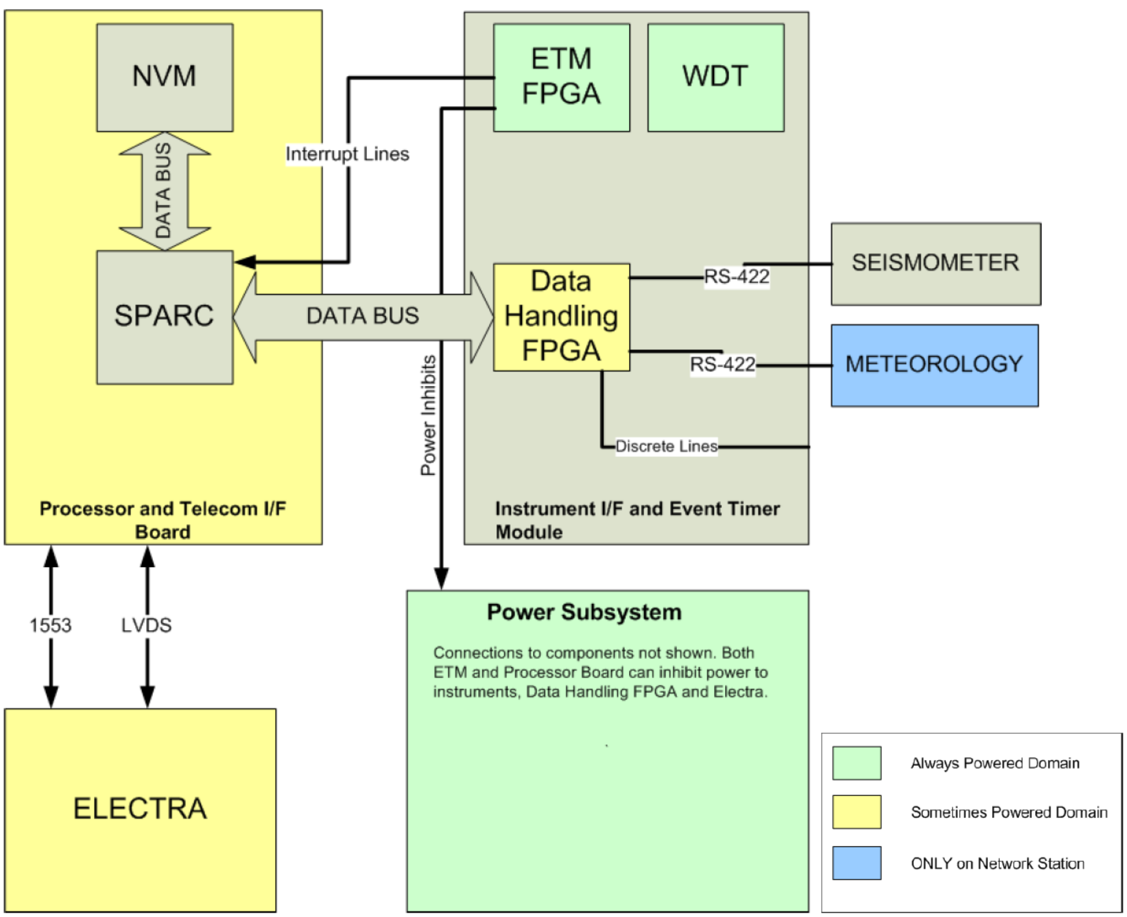

Figure 3-3. Network Pathfinder and Drop Package Avionics Design

3.2.4 Seismic Drop Package

The Seismic Drop Package (Figure 3-4) would be a fixed scientific package with a single instrument. It would be carried on the proposed MAX-C Rover and dropped on the surface at a suitable location sometime during the first 15 months of the mission. The Seismic Drop Package would be solar-powered, with a design life of 3 months after it is dropped on the surface. The system is a single-string design and carries 43% mass and power contingencies.

3.2.4.1 Instrument Payload Description

The Seismic Drop Package would contain only one science instrument, a single-axis seismometer (Table 3-5). This seismometer would operate in conjunction with the seismometer on the proposed Network Pathfinder to measure the local crustal thickness.

3.2.4.2 Flight System

Table 3-6 provides the preliminary estimates for the flight system subsystem masses, subsystem power in each operational mode, total mass and power, and margins.

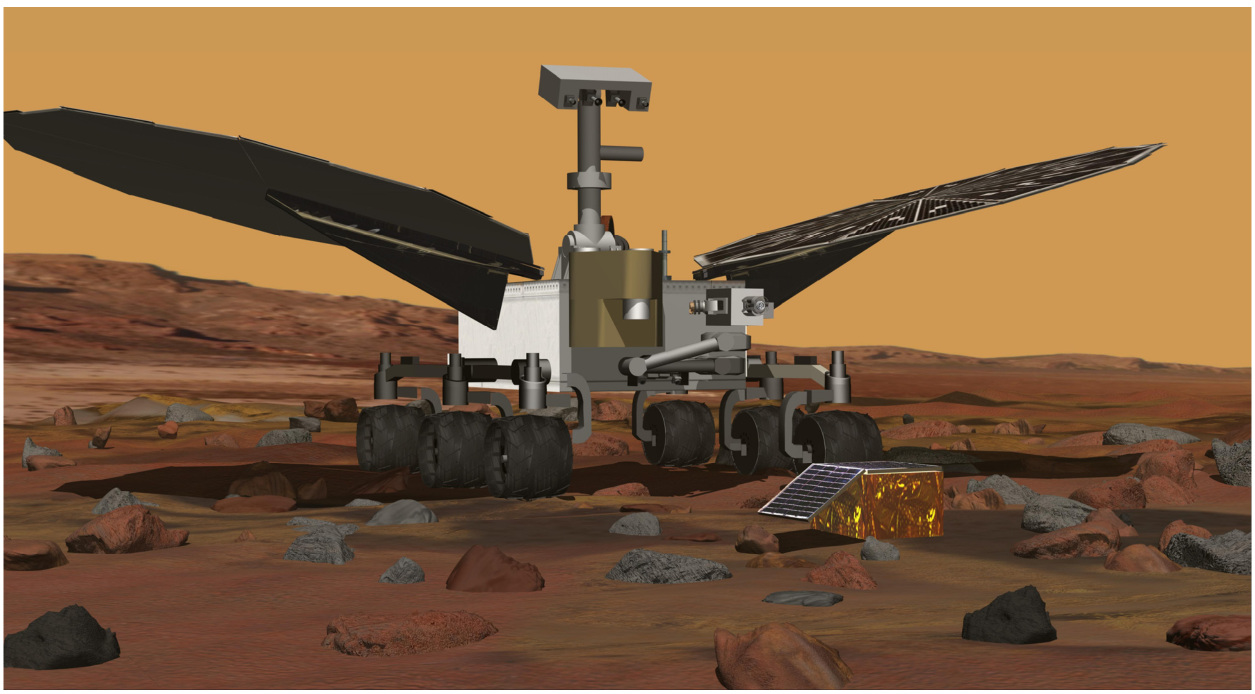

Figure 3-4. Artist's Conception of the Seismic Drop Package (Foreground), after Deployment on the Surface by the Proposed MAX-C Rover

Table 3-5. Seismic Drop Package Payload Mass and Power Preliminary Estimates

	Mass			Average Power			Data Rate^		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)	CBE (kbps)	% Cont.	MEV (kbps)
Seismometer (1-axis)	0.8	30%	1	1	30%	1.3	10	30%	13

^Instrument data rate defined as science data rate prior to on-board processing

Table 3-6. Seismic Drop Package Mass and Power Preliminary Estimates

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Science during day	Mode 2 Power (W) Science with telecom	Mode 3 Power (W) Safe	Mode 4 Power (W) Night
Power Mode Duration (hours per sol)					*10.4333*	*0.16667*	*24.6*	*14*
Payload on this Element								
Instruments	3%	0.8	30%	1.0	1	1	0	1
Payload Total	3%	**0.8**	30%	**1.0**	**1**	**1**	**0**	**1**
Spacecraft Bus		do not edit formulas below this line, use the calcualtions and override tables ins						
Attitude Control	0%	0.0	0%	0.0	0	0	0	0
Command & Data	14%	3.7	30%	4.8	2	8	2	2
Power	34%	9.0	30%	11.7	2	9	3	3
Propulsion1	0%	0.0	0%	0.0	0	0	0	0
Structures & Mechanisms	19%	5.1	30%	6.6	0	0	0	0
S/C-Side Adapter	0%	0.0	30%	0.0				
Cabling	13%	3.3	30%	4.3				
Telecom	12%	3.1	3%	3.2	0	70	0	0
Thermal	6%	1.5	0%	1.5	2	2	2	2
Bus Total		25.6	25%	32.0	5	89	6	6
Thermally Controlled Mass				32.0				
Spacecraft Total (Dry)		26.4	25%	33.0	5	89	6	6
Subsystem Heritage Contingency		6.6	25%	25%				
System Contingency		4.7	18%	18%	2	38	2	3
Spacecraft with Contingency		**38**	of total	w/o addl pld	**7**	**128**	**8**	**9**
Spacecraft Total (Wet)		**38**						

Structure. The Seismic Drop Package would have a simple structure necessary for supporting telecom, power, and thermal hardware. The resulting design was scoped as a simple enclosure structure. The drop package was treated as a black box that simply needed to be separated from the rover. A single-hinge solar array would be deployed after the package is dropped on the surface.

Hardware items would include a support structure in the form of an external enclosure, a separation mechanism for detaching from the proposed MAX-C Rover, and a simple deployment mechanism to release a passively deployed single-hinge solar array.

Thermal Control. The thermal control baseline for the Seismic Drop Package would include thermal insulation and five RHUs. Thermal insulation, which would be similar to MSL thermal insulation and has a mass density similar to MLI, would use the MLI layers to minimize thermal convection so that the insulation properties of the martian atmosphere, which is CO_2 at a pressure of ~8 torr, would be maximized.

The RHUs would be used to provide thermal energy to the Seismic Drop Package to maintain it within operational limits. The proposed MAX-C Rover would deploy the Seismic Drop Package at some distance from the landing pallet. The thermal control would require five RHUs as well as the insulation blanket to provide the thermal isolation and thermal energy to maintain it within operational temperature levels.

Telecom. The Seismic Drop Package would have its own UHF telecom system for communicating with an orbiting Mars asset. It would carry an Electra Lite UHF transponder and a UHF quad-helix antenna, which are identical to those on the proposed MAX-C Rover. No new hardware would be required for the Seismic Drop Package.

Command & Data Handling. The Seismic Drop Package would have interfaces with the Electra-telecom interface and a seismometer. Since the instrument could take and store data without involving the avionics, a custom SPARC processor board and an ETM/instrument interface card would maximize functionality and flexibility while preserving power and mass margins.

The avionics would only be required to manage telecom data transfer. The ETM would an always-powered domain and would be responsible for waking up the SPARC processor to manage data transfer

from instruments to the Electra-radio. The "sometimes-powered" domain of the ETM board would include an FPGA to help configure the instrument interfaces and manage data transfer.

Figure 3-3 shows the avionics design for the proposed Seismic Drop Package.

Power. The power subsystem for the Seismic Drop Package would consist of a rigid 0.3 m^2 TJ GaAs solar array, a 12 A-hr Li ion battery and electronics (array switch card and a custom ETM). The solar array was sized to provide 80 W-hrs per sol at EOL (45 sols) to support the science and telecom operations during the day and battery recharge. The design assumed an atmospheric opacity (tau) of 0.5 and a dust accumulation rate of 10% per 100 sols (consistent with MER observations). The design examined the solar availability at 25 N and 15 S latitude over the course of 45 sols and was sized for the worst case. The first sol of the 45 sol mission was varied at each latitude to take advantage of the martian seasons and to start at a time of greater solar insolation. The battery was sized to support nighttime instrument operations with a maximum depth of discharge of 36%. The custom ETM would be a new development for this mission, but the rest of the power subsystem design has MER and MSL heritage.

3.2.5 Subsurface Station

The proposed Subsurface Station (Figure 3-5) would be a fixed scientific package with a drill, sample handling, sample caching, and a substantial set of instruments. It would be mounted on the Landing Pallet, which would deliver it to the martian surface on a Sky Crane entry system. The Subsurface Station would be solar-powered, with a design life of 18 months on the surface. The system is a single-string design and carries 43% mass and power contingencies.

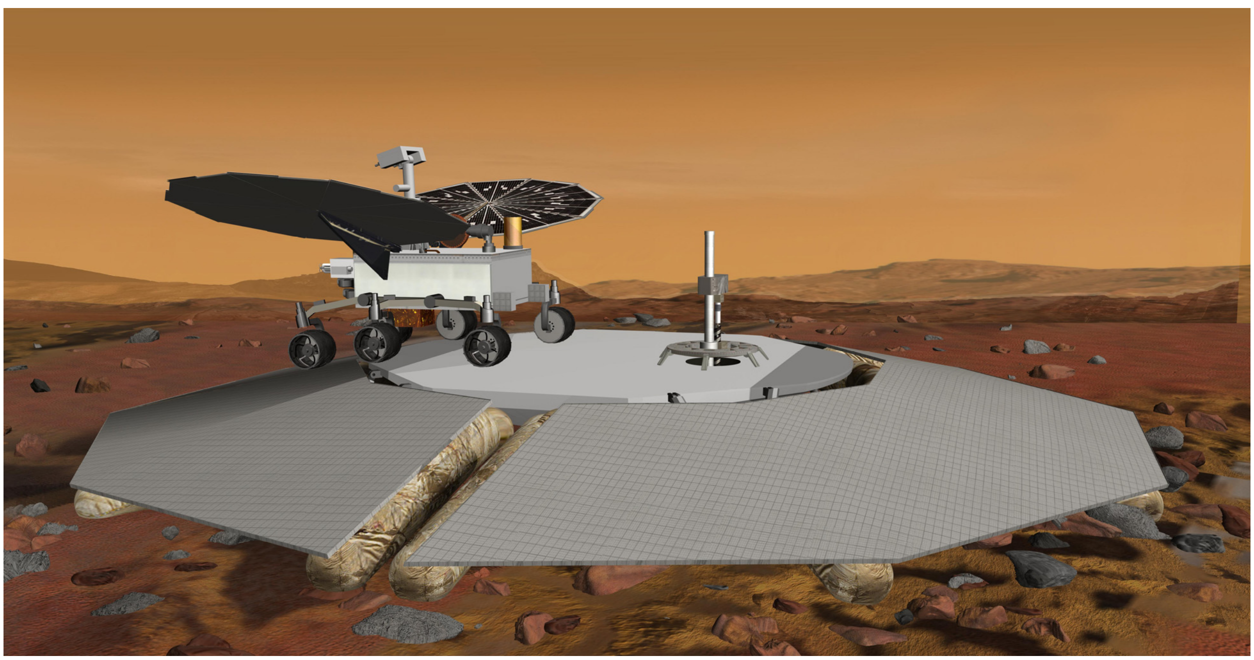

Figure 3-5. Artist's Conception of the Proposed Subsurface Station Attached to the Landing Pallet (The drill system can be seen to the right of the MAX-C Rover.)

3.2.5.1 Instrument Payload Description

The proposed Subsurface Station payload was selected to be similar in scientific capability to the payload on the ExoMars Rover. This was done to allow the trade of a mobile vs. fixed subsurface geology/astrobiology pathway with functionally equivalent payloads. However, the Subsurface Station payload (Table 3-7) was scoped in mass and power using typical NASA mission instruments and not the highly integrated payload on ExoMars. Thus, the preliminary mass and power estimates provided below will typically be higher than those for the ExoMars instruments. Where possible, instruments identical to those used on the proposed MAX-C Rover were used.

A drill would allow for sample collection and preparation for in-situ measurements. The samples would be stored in a primary and contingency pair of sample caches. These caches would potentially be collected during a subsequent mission by a fetch rover for return to a Mars ascent vehicle for eventual return to Earth.

The impacts of adding two more simple instruments were not considered significant to the design; therefore, the proposed Subsurface Station was designed to carry the instruments from the Network Pathfinder. The same mass, power, and cost number were used for the seismometer and meteorological package.

The heart of the payload would be a system capable of drilling at least two meters into the martian regolith. This system was sized based on data from a set of studies previously conducted by the Mars Program Office. The 50 kg number was an upper bound from these studies for a flight article.

The sample handling and caching, the Raman spectrometer, the IR spectrometer, and the cameras were estimated using equivalent instruments from proposed MAX-C. The drill hole IR spectrometer and the Mars organic instrument were estimated based on their equivalents on ExoMars.

3.2.5.2 Flight System

Table 3-8 provides the preliminary estimates for flight system subsystem masses, subsystem power in each operational mode, total mass and power, and margins.

Table 3-7. Subsurface Station Payload Mass and Power Preliminary Estimates

	Mass			Op. Power			Data Rate^
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)	CBE (kbps)
Seismometer	7.5	30%	9.8	3	30%	4	10
Meteorological package	2.5	30%	3.25	1.5	30%	2	3
Lander cameras	0.3	2%	0.31	2	30%	3	2,400
Arm camera	1.6	2%	1.6	7	30%	9	2,400
Sample insertion camera	0.3	2%	0.31	2	30%	3	2,400
Descent cameras	0.3	2%	0.31	2	30%	3	2,400
2 meter drill	50	30%	65	150	30%	195	1
Raman spectrometer	5	30%	6.5	30	30%	39	100
IR spectrometer	3.5	30%	4.6	20	30%	26	2,400
Drill hole IR spectrometer	0.7	30%	0.9	10	30%	13	2,400
Mars organic instrument	6.1	30%	7.9	25	30%	33	100
Cache sample handling & container	9	30%	11.7	10	30%	13	1
Total Payload	**86.8**	**–**	**112.14**	**–**	**–**	**–**	**–**

^Instrument data rate defined as science data rate prior to on-board processing

Note: See Flight System mass and power table for average power use in each operational mode.

Table 3-8. Subsurface Station Mass and Power Preliminary Estimates

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Drill	Mode 2 Power (W) Sample Analysis	Mode 3 Power (W) Seismometer and met package	Mode 4 Power (W) Telecom	Mode 5 Power (W) Safe	Mode 6 Power (W) Night
Power Mode Duration (hours/sol)					*1*	*1*	*8.43*	*0.167*	*24.6*	*14*
Payload on this Element										
Instruments	52%	87.1	29%	112.4	165	80	5	5	0	5
Payload Total	52%	**87.1**	29%	**112.4**	**165**	**80**	**5**	**5**	**0**	**5**
Spacecraft Bus		do not edit formulas below this line, use the calcualtions and override tables instead -->								
Attitude Control	0%	0.0	0%	0.0	0	0	0	0	0	0
Command & Data	8%	12.5	7%	13.4	53	53	53	53	53	53
Power	9%	15.6	30%	20.3	16	9	3	8	3	3
Propulsion1	0%	0.0	0%	0.0	0	0	0	0	0	0
Structures & Mechanisms	20%	32.8	30%	42.6	0	0	0	0	0	0
S/C-Side Adapter	0%	0.0	30%	0.0						
Cabling	7%	11.1	30%	14.5						
Telecom	2%	3.6	3%	3.7	0	0	0	70	0	0
Thermal	2%	3.6	0%	3.6	5	5	5	5	5	5
Bus Total		79.2	24%	98.0	73	66	61	136	60	60
Thermally Controlled Mass				98.0						
Spacecraft Total (Dry)		166.3	27%	210.5	238	146	65	141	60	65
Subsystem Heritage Contingency		44.2	27%	27%						
System Contingency		27.3	16%	16%	102	63	28	61	26	28
Spacecraft with Contingency		**238**	of total	w/o addl pld	**341**	**209**	**93**	**201**	**86**	**93**
Spacecraft Total (Wet)		**238**	Dry Mass for Prop Sizing		238					

Structure. The proposed Subsurface Station would be mounted on the landing pallet.

A major requirement for the structure would be to deploy and support the two meter drill and accompanying sample handling system. When in operation, the drill would be raised from a horizontal position to a vertical position and pass through a hole in the pallet in order to reach the martian surface. The drilling surface preparation hardware would be comprised of two actuators (one to lower the drill to the surface and another to prepare the sample location) and 5 kg of additional structure mass. The entirety of the drill and measurement equipment must also be kept free of contamination.

The proposed Subsurface Station would have a simple structure necessary for supporting telecom, power, and thermal hardware. The resulting design was scoped as a simple enclosure structure. Solar array area for the Subsurface Station could be acquired using the top deck of the landing pallet or a deployable solar array.

Thermal Control. The baseline thermal control for the proposed Subsurface Station would include thermal insulation and one RHU. Thermal insulation, which would be similar to MSL thermal insulation and has a mass density similar to MLI, would use the MLI layers to minimize thermal convection so that the insulation properties of the martian atmosphere, which is CO_2 at a pressure of ~8 torr, would be maximized. The Subsurface Station would be mounted on the pallet, and with the pallet thermal control, the use of CO_2 insulation, and the RHU, the Subsurface Station would be maintained within operational limits.

Telecom. The proposed Subsurface Station would have its own UHF telecom system for communicating with an orbiting Mars asset. It would carry an Electra Lite UHF transponder and a UHF quad-helix antenna, which are identical to those on the proposed MAX-C Rover. No new hardware would be required for the Subsurface Station.

Command & Data Handling. The proposed Subsurface Station would use similar avionics to the MAX-C Rover. It would include many of the instruments from the rover, in addition to a few other instruments. Because the stationary platform would not require it, this option does not have the distributed motor controller card. The large number of instrument interfaces for the stationary platform would make MSAP components an easy alternative to developing custom avionics. In addition, keeping the cards the same as the rover elements would allow a second string of the rover to be built. This would save non-recurring engineering costs that a new development would incur. The standard MSAP configuration includes a RAD750, a critical relay control card (CRCC), a non-volatile memory and camera card (NVMCAM), a telecom interface card (MTIF), serial interface assembly (MSIA), a motor control interface card (MCIC), remote engineering units (REU), and power converters. Figure 3-6 shows the avionics design for the Subsurface Station.

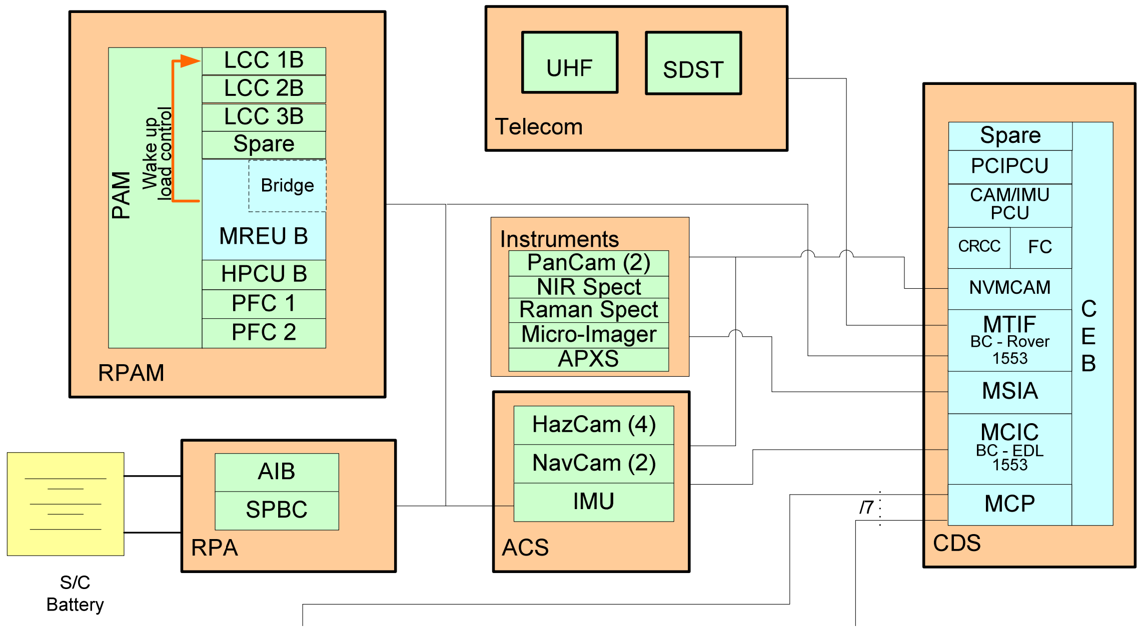

Figure 3-6. Subsurface Station Avionics Design

Power. The power subsystem for the proposed Subsurface Station would consist of a rigid 2.41 m_2 TJ GaAs solar array, and two 50 A-hr Li ion batteries and electronics (array switch card and a custom ETM). The solar array was sized to provide 640 W-hrs per sol at the end of 18 months to support drilling and mission operations during the day and battery recharge; it is assumed that the drilling activity would be complete at the end of 18 months. The design assumed an atmospheric opacity (tau) of 0.5 and a dust accumulation rate of 10% per 100 sols (consistent with MER observations). The design examined the solar availability at 25 N and 15 S latitude over the course of 18 months and was sized for the worst case. The battery was sized to support nighttime instrument operations with a maximum depth of discharge of 51%. The custom ETM would be a new development for this mission, but the rest of the power subsystem would have MER and MSL heritage.

3.3 Mission Architecture Study Results

3.3.1 Overview

After completion of the detailed point designs, the JPL architecture team was able to address the purpose of the study—to “explore the full range of science capabilities that could be delivered to the surface of Mars in 2018 by a MSL-derived Sky Crane EDL system [1].” To streamline the architecture assessment, the results of the MAX-C study were used to size the Sky Crane, the landing pallet, and the MAX-C and ExoMars Rovers. The delivery capability of the MSL-derived landing system was fixed at the 1,050 kg from the MAX-C mission concept study report [3]. Combinations of elements were then analyzed for their ability to fit on the Sky Crane system and costed based on the Team X models.

3.3.2 Key Trades

The key trades in this study involved looking at various combinations of mission elements for the three science pathways and choice of mobile vs. fixed option. Table 3-9 shows combinations of the mission elements and the four that were selected for detailed study (highlighted in gray).

Table 3-9. Potential Missions for Sky Crane Delivery

Pathway Mission	Surface Field Geology/ Astrobiology	Subsurface Geology/ Astrobiology	Network Science	Comments
Baseline	MAX-C Rover	ExoMars Rover	None	Baseline MAX-C Mission
Option 2	MAX-C Rover	ExoMars Rover	Network Pathfinder	Adds network science to the Baseline Mission
	MAX-C Rover	ExoMars Rover	Network Pathfinder and Seismic Drop Package	Does not fit within Sky Crane capabilities
Option 3	MAX-C Rover	None	Network Pathfinder and Seismic Drop Package	Drops subsurface pathway for network science
	MAX-C Rover	None	Network Pathfinder	Trivial change to Option 3; removes Seismic Drop Package
Option 4	MAX-C Rover	Subsurface Station	Network Pathfinder	Subsurface Station includes Network Pathfinder science
	MAX-C Rover	Subsurface Station	Network Pathfinder and Seismic Drop Package	Trivial change to Option 4; adds Seismic Drop Package
	MAX-C Rover	None	None	Costs same as Baseline Mission

3.3.3 Set of Missions Studied

The missions studied in some detail are described below.

3.3.3.1 Baseline Mission: MAX-C & ExoMars

The MAX-C Baseline Mission only addresses two of the three science pathways: the surface field geology / astrobiology pathway and the subsurface geology/astrobiology pathway. The total mission estimate comes in at 992 kg of mass, within the capabilities of the MSL-derived Sky Crane. See the MAX-C mission concept study report for more details [3]. Table 3-10 shows the carried elements, pallet lander subsystem masses, and margins for the Baseline Mission.

3.3.3.1.1 Risk List

The top five risks are identified in the MAX-C mission concept study report [3].

3.3.3.2 Option 2: MAX-C, ExoMars, and Network Pathfinder

Option 2 adds the Network Pathfinder to the Baseline Mission. This would allow this mission to address all three science pathways: the surface field geology/astrobiology pathway, the subsurface geology/astrobiology pathway, and the network science pathway.

The total mission estimate comes in at 1,066 kg of mass, which is slightly larger than the 1,050 kg estimated capabilities of the MSL-derived Sky Crane. This is 2% of the delivered mass. At this level of understanding, this is not enough of a difference to exclude this scientifically attractive mission. Potential adjustments, including merging the Network Pathfinder and pallet structure, could very well reduce this mass to within the Sky Crane capabilities. This option is recommended for further study. Table 3-11 shows the carried elements, pallet lander subsystem masses, and margins for Option 2.

3.3.3.2.1 Risk List

The top five risks are the same as in the Baseline Mission and are identified in the MAX-C mission concept study report [3].

Table 3-10. MAX-C and ExoMars Surface Mass Preliminary Estimates

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)
Elements Carried by the Landing Pallet				
MAX-C Rover	33%	254.9	43%	364.5
EXO Mars Rover	38%	300.0	0%	300.0
Carried Elements Total	71%	554.9	20%	664.5
Spacecraft Bus			do not edit formulas below tl	
Attitude Control	0%	0.6	10%	0.7
Command & Data	0%	0.0	0%	0.0
Power	1%	7.0	30%	9.1
Propulsion1	0%	0.0	0%	0.0
Structures & Mechanisms	27%	209.3	30%	272.1
Cabling	1%	11.3	30%	14.7
Telecom	0%	0.0	0%	0.0
Thermal	0%	0.7	6%	0.8
Bus Total		229.0	30%	297.4
Thermally Controlled Mass				297.4
Spacecraft Total (Dry)		783.9	23%	961.9
Subsystem Heritage Contingency		178.0	23%	78%
System Contingency		30.1	4%	13%
Spacecraft with Contingency		992	of total	w/o addl pld
Spacecraft Total (Wet)		992		
MSL Skycrane Capability		1050		
Launch Vehicle Margin		58.0	6%	
JPL Design Principles Margin		35%		

Table 3-11. MAX-C, ExoMars, and Network Pathfinder Surface Mass Preliminary Estimates

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)
Elements Carried by the Landing Pallet				
MAX-C Rover	31%	254.9	43%	364.5
EXO Mars Rover	36%	300.0	0%	300.0
Network Station	6%	51.8	43%	74.1
Carried Elements Total	73%	606.7	22%	738.6
Spacecraft Bus			do not edit formulas below tl	
Attitude Control	0%	0.6	10%	0.7
Command & Data	0%	0.0	0%	0.0
Power	1%	7.0	30%	9.1
Propulsion1	0%	0.0	0%	0.0
Structures & Mechanisms	25%	209.3	30%	272.1
Cabling	1%	11.3	30%	14.7
Telecom	0%	0.0	0%	0.0
Thermal	0%	0.7	6%	0.8
Bus Total		229.0	30%	297.4
Thermally Controlled Mass				297.4
Spacecraft Total (Dry)		835.7	24%	1036.0
Subsystem Heritage Contingency		200.3	24%	87%
System Contingency		30.1	4%	13%
Spacecraft with Contingency		1066	of total	w/o addl pld
Spacecraft Total (Wet)		1066		
MSL Skycrane Capability		1050		
Launch Vehicle Margin		-16.0	-2%	
JPL Design Principles Margin		29%		

3.3.3.3 Option 3: MAX-C, Network Pathfinder, and Seismic Drop Package

Option 3 removes the ExoMars Rover and adds the Network Pathfinder and Seismic Drop Package. This mission would only address two of the three science pathways: the surface field geology/astrobiology pathway and the network science pathway. The total mission estimate comes in at 801 kg of mass, well within the capabilities of the MSL-derived Sky Crane. Table 3-12 shows the carried elements, pallet lander subsystem masses and margins for Option 3.

3.3.3.3.1 Risk List

The top five risks are the same as in the Baseline Mission and are identified in the MAX-C mission concept study report [3].

3.3.3.4 Option 4: MAX-C, Subsurface Station

Option 4 removes the ExoMars Rover and adds the proposed Subsurface Station. Note that the Subsurface Station would include the Network Pathfinder instruments; therefore, this mission would address all three science pathways: the surface field geology/astrobiology pathway, the subsurface geology/astrobiology pathway, and the network science pathway. The total mission estimate comes in at 933 kg of mass, within the capabilities of the MSL-derived Sky Crane. Table 3-13 shows the carried elements, pallet lander subsystem masses and margins for Option 4.

3.3.3.4.1 Risk List

The top five risks are the same as in the Baseline Mission and are identified in the MAX-C mission concept study report [3].

Table 3-12. MAX-C, Network Pathfinder, and Seismic Drop Package Surface Mass Preliminary Estimates

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)
Elements Carried by the Landing Pallet				
MAX-C Rover	46%	254.9	43%	364.5
Network Station	9%	51.8	43%	74.1
Drop Package	4%	24.4	43%	34.9
Carried Elements Total	59%	**331.1**	43%	**473.5**
Spacecraft Bus			do not edit formulas below t	
Attitude Control	0%	0.6	10%	0.7
Command & Data	0%	0.0	0%	0.0
Power	1%	7.0	30%	9.1
Propulsion1	0%	0.0	0%	0.0
Structures & Mechanisms	37%	209.3	30%	272.1
Cabling	2%	11.3	30%	14.7
Telecom	0%	0.0	0%	0.0
Thermal	0%	0.7	6%	0.8
Bus Total		229.0	30%	297.4
Thermally Controlled Mass				297.4
Spacecraft Total (Dry)		560.1	38%	770.9
Subsystem Heritage Contingency		210.8	38%	92%
System Contingency		30.1	5%	13%
Spacecraft with Contingency		**801**	of total	w/o addl pld
Spacecraft Total (Wet)		**801**		
MSL Skycrane Capability		**1050**		
Launch Vehicle Margin		**249.0**	24%	
JPL Design Principles Margin		**47%**		

Table 3-13. MAX-C and Subsurface Station Surface Mass Preliminary Estimates

	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)
Elements Carried by the Landing Pallet				
MAX-C Rover	39%	254.9	43%	364.5
Subsurface Package	26%	168.8	43%	241.4
Carried Elements Total	65%	**423.7**	43%	**605.9**
Spacecraft Bus			do not edit formulas below t	
Attitude Control	0%	0.6	10%	0.7
Command & Data	0%	0.0	0%	0.0
Power	1%	7.0	30%	9.1
Propulsion1	0%	0.0	0%	0.0
Structures & Mechanisms	32%	209.3	30%	272.1
Cabling	2%	11.3	30%	14.7
Telecom	0%	0.0	0%	0.0
Thermal	0%	0.7	6%	0.8
Bus Total		229.0	30%	297.4
Thermally Controlled Mass				297.4
Spacecraft Total (Dry)		652.7	38%	903.3
Subsystem Heritage Contingency		250.6	38%	109%
System Contingency		30.1	5%	13%
Spacecraft with Contingency		**933**	of total	w/o addl pld
Spacecraft Total (Wet)		**933**		
MSL Skycrane Capability		**1050**		
Launch Vehicle Margin		**116.7**	11%	
JPL Design Principles Margin		**38%**		

3.4 Concept of Operations and Mission Design

Launch, cruise, and entry operations would be similar to MSL operations.

Surface operations for the proposed MAX-C Rover would be similar to the MER/MSL model. The operations support would be 24/7 for the first 90 days, shifting to regular five-day work weeks for the remainder of the surface science operations. The Subsurface Station would be operated in a similar manner. Operations would cover 500 sols.

Surface operations for the Network Pathfinder would be 24/7 through the deployment phase and initial operations. Since the instruments are basically turned on to collect data, further operations would consist of weekly commanding. The designed operational lifetime is 18 months.

The Seismic Drop Package would be carried by the MAX-C Rover until it is deployed onto the surface. It then would have a 3-month designed operational lifetime. After initial deployment, the package would be commanded on a weekly basis. The Network Pathfinder and Seismic Drop Package were assumed to be operated by a common team.

3.4.1 Design Details

All data associated with major science operations would be relayed to Earth via orbiter. The data would be at least 95% complete with a latency of no longer than 7 sols. Limited, critical data would be ~99.9% complete. Typical latency for data would be on the order of 24 hours; some data types, e.g., driving, would have a shorter average latency time of approximately 12 hours.

It is expected that the proposed MAX-C Rover would transmit approximately 269.5 Mbits per sol via two passes to the orbiter using the UHF link. The DSN would transmit daily commands to the vehicle directly

across the X-band link; the commands and file updates would not exceed ~3.5 Mbits per day. In addition, once per month the vehicle's clock would be updated and other routine updates would be performed via Earth command.

The proposed Subsurface Station is assumed to have an equivalent number of instruments to the rover, with an equivalent data volume, requiring a doubling of relay contact time. In the Subsurface Station option containing both the rover and the station, an equivalent data volume for the station was assumed, requiring double the DSN allocations for the relay of the science data for surface operations.

Commanding of the Subsurface Station, the Network Pathfinder, and the Seismic Drop Package would be via UHF uplink. This capability, while not frequently used, has been demonstrated on MER.

The operations would be a mission-specific implementation of the JPL mission operations and ground systems as used previously for the MSL mission. Standard JPL operations processes and procedures would be used. The different configurations and instruments on the proposed rover and substation package would require new spacecraft models and flight rules to support sequence tools, as well as new telemetry formats. The simultaneous operation of the two crafts in the Subsurface Station option requires additional operations team support as well as additional modifications to the ground systems to handle scheduling and processing of double the telemetry streams.

The mission operations would include processing to Level 0 data and maintaining it for the life of the mission. Further processing and archiving would be the responsibility of the science operations. For costing, operations were assumed to be conducted at JPL.

Mission design would be the same as in the proposed MAX-C mission concept study report and is not duplicated here [3].

3.5 Planetary Protection

The Team X process designs the mission to meet the planetary protection category recommended by the Team X Planetary Protection chair. At this level of design, it is not appropriate to discuss options and costs for meeting these requirements.

4. Development Schedule and Schedule Constraints

4.1 High-Level Mission Schedule

Figure 4-1 shows the overall high-level mission schedule. It is based on data provided to Team X by the MAX-C study team. The proposed Subsurface Station has about the same complexity as the MAX-C Rover, so a similar schedule was assumed. The Network Pathfinder and the Seismic Drop Package are both simpler than the proposed MAX-C Rover, but since the missions of which they would be a part include the MAX-C Rover, the longer rover schedule was used.

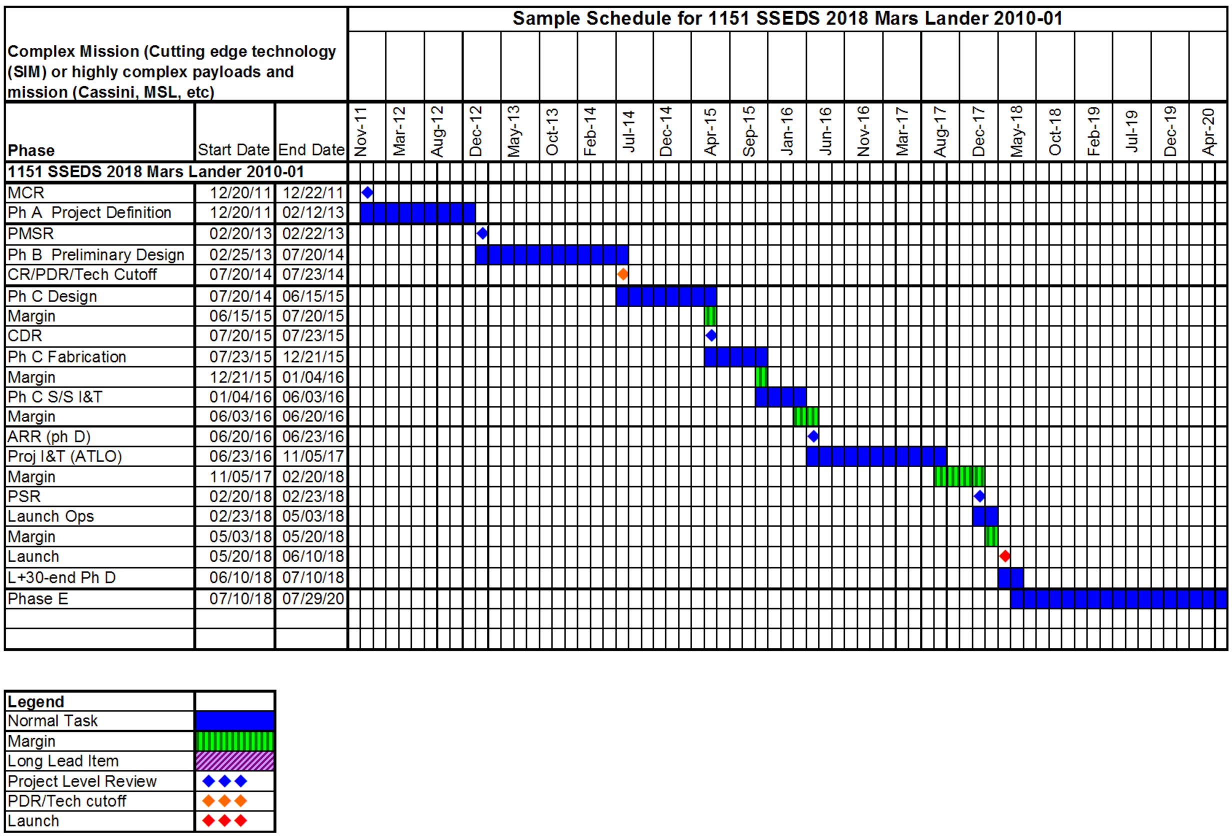

Figure 4-1. High-Level Mission Schedule

4.2 Technology Development Plan

The following scheduled dates would have a direct impact on any technology maturation plan:

- Mission PDR/Technology Cut-Off Date: July 20, 2014
- Mission CDR: July 20, 2015
- Mission Acceptance Readiness Review (ARR): June 20, 2016

Since this study has identified no required new technologies beyond those provided in the MAX-C report [3], no technology development plan is provided.

4.3 Development Schedule and Constraints

The launch readiness date (LRD) is tentatively scheduled for May 20, 2018. The anticipated launch window would extend from the LRD to June 10, 2018.

5. Mission Life-Cycle Cost

5.1 Cost Estimate Interpretation Policy, Reserves, and Accuracy

Team X guidelines for this study were to provide independent design and costing analysis for each mission concept. The cost estimates summarized in this document were generated as part of a Pre-Phase-A preliminary concept study, are model-based, were prepared without consideration of potential industry participation, and do not constitute an implementation-cost commitment on the part of JPL or the California Institution of Technology (Caltech). The accuracy of the cost estimate is commensurate with the level of maturity of the mission concept, and should be viewed as indicative rather than predictive.

5.2 Costing Methodology and Basis of Estimate

The cost estimation process begins with the customer providing the base information for the cost estimating models and defining the mission characteristics, such as:

- Mission architecture
- Payload description
- Master equipment list (MEL) with heritage assumptions
- Functional block diagrams
- Spacecraft/payload resources (mass [kg], power [W], …)
- Phase A–F schedule
- Programmatic requirements
- Model specific inputs

JPL has created 33 subsystem cost models, each owned, developed, and operated by the responsible line organizations. These models are customized and calibrated using actual experience from completed JPL planetary missions. The models are under configuration management control and are utilized in an integrated and concurrent environment, so the design and cost parameters are linked.

5.3 Cost Estimates

Cost estimates for the missions are provided below in FY15 dollars. An end-to-end mission cost is provided for each of the four missions studied and includes all elements of the potential mission. Costs are for representative payloads and flight elements. Note that this is a CML-3–4 analysis; therefore, costs should be considered representative and will likely change as the mission concepts are further defined.

The baseline for costing was the overall 2018 mission from the MAX-C mission concept study report [3], which consists of the cruise, entry, descent, landing pallet and MAX-C Rover elements (plus the contributed ExoMars Rover). Total estimated cost for this mission is $2.2 billion.

The second mission (Option 2) has the baseline with the Network Pathfinder added. Total cost for this mission is estimated at $2.4 billion. The cost increased $150 M from the Baseline Mission, due to the addition of the Network Pathfinder. Key additional costs for the Network Pathfinder were the instrumentation ($52M), the flight system ($36M), plus wrap costs and reserves.

The third mission (Option 3) has the baseline minus the ExoMars Rover, with the Network Pathfinder and Seismic Drop Package added. Total estimated cost for this mission is $2.4 billion. The cost increased $50 M

from Option 2, due to the addition of the Seismic Drop Package. Key additional costs for the Seismic Drop Package were the instrumentation ($17M), the flight system ($15M), plus wraps and reserves.

The final mission (Option 4) has the baseline minus the ExoMars Rover, with the Network Pathfinder and Subsurface Station added. Total cost for this mission is estimated at $2.9 billion. The cost increased $650 M from Option 2, due to the addition of the Subsurface Station. Key additional costs for the Subsurface Station were the instrumentation ($185M), the flight system ($113M), plus wraps and reserves.

Technology costs run approximately $85 million in all options, based on the technologies required for MAX-C. See the MAX-C mission concept study report for details [3].

Appendix A. Acronyms

APXS	Alpha-Particle-X-Ray Spectrometer
ARR	Acceptance Readiness Review
BOL	beginning of life
CBE	current best estimate
CDR	Critical Design Review
CRCC	critical relay control card
DSN	Deep Space Network
EDL	entry, descent, and landing
EM	electromagnetic
EOL	end of life
ESA	European Space Agency
ETM	event timer module
FPGA	field programmable gate array
FY	fiscal year
HGA	high gain antenna
IMU	inertial measurement unit
LGA	low gain antenna
LIBS	laser-induced breakdown spectroscopy
LRD	launch readiness date
MA_MISS	Mars multispectral imager for subsurface studies
MAX-C	Mars Astrobiology Explorer-Cacher
MB	Mössbauer Spectrometer
MCIC	motor control interface card
MEL	master equipment list
MER	Mars Exploration Rover
MEV	maximum expected value
MI	Microscopic Imager
MLI	multi-layer insulation
MOLA	Mars Orbiter Laser Altimeter
MOMA	Mars organic molecule analyzer
MSIA	mulitmission serial interface assembly
MSL	Mars Science Laboratory
MTIF	multimission telecom interface card
NIR	near infrared
NVMCAM	non-volatile memory and camera card
PDR	Preliminary Design Review
RAT	rock abrasion tool
REU	remote engineering units
RHU	radioisotope heater units
RY	real year
SDST	small deep space transponder
SHEC	sample handling, encapsulation, and containerization
UHF	ultra-high frequency
WEB	warm electronics box
WISDOM	Water Ice and Subsurface Deposit Information On Mars
XRD	X-ray diffractometer

Appendix B. References

[1] "Decadal Survey directions to study team, provided in hardcopy." Fall 2009.

[2] European Space Agency. Update 05 February 2010. "The Exomars Instrument Suite." http://exploration.esa.int/science-e/www/object/index.cfm?fobjectid=45103

[3] National Aeronautics and Space Administration. March 2010. Mission Concept Study: Planetary Science Decadal Survey—Mars 2018 MAX-C Caching Rover.